Early Journal Content on JSTOR, Free to Anyone in the World

This article is one of nearly 500,000 scholarly works digitized and made freely available to everyone in the world by JSTOR.

Known as the Early Journal Content, this set of works include research articles, news, letters, and other writings published in more than 200 of the oldest leading academic journals. The works date from the mid-seventeenth to the early twentieth centuries.

We encourage people to read and share the Early Journal Content openly and to tell others that this resource exists. People may post this content online or redistribute in any way for non-commercial purposes.

Read more about Early Journal Content at http://about.jstor.org/participate-jstor/individuals/early-journal-content.

JSTOR is a digital library of academic journals, books, and primary source objects. JSTOR helps people discover, use, and build upon a wide range of content through a powerful research and teaching platform, and preserves this content for future generations. JSTOR is part of ITHAKA, a not-for-profit organization that also includes Ithaka S+R and Portico. For more information about JSTOR, please contact support@jstor.org.

XXVIII.

COLOR-PERCEPTION.

By G. Stanley Hall.

Presented March 14, 1878.

THE finest distinctions which the ear can make — whether in detecting differences as small as one sixty-fourth of a whole note, or between harmonic upper partial tones — are, at first, purely mechanical processes of the terminal apparatus of the auditory nerve. Only after this process is complete, does the neural process of the extremely specialized fibres, which ends in the sensation of tone, begin. The physicist can follow the sound waves as they are conducted through the outer media of the ear, as their amplitude is diminished and their force increased; can calculate the amount of sympathetic vibration which will be caused in each part of the organism, as it passes; and at last determine the formulæ by which it is analyzed into pendular vibrations, by the organs of Corti or the fibres of the basilar membrane: thus tracing it to the very verge of consciousness itself.

In turning to the perception of color, we find that, if we take into account the analogies suggested by the undulatory theory, and the greater minuteness of the waves of the light-ether, the eye — so far as explored — responds to external stimulation with far less special mechanical adaptation than the ear. Masses of white light are thrown upon the retina, the focal distance of the various colors of which it is composed differing by twice the whole retinal diameter and six times the length of the longest rods, — every outline surrounded by dispersive and diffractive fringes, of ten times the diameter of the base of one cone; and here, with a vaguely defined, and to a great extent unverified, suggestion of three species of percipient elements, it is left.

If this were really all, and neural action had to collect the material of visual sensation in this form, and the mind, reacting upon such aggregate stimuli, were able to project the whole visible universe of color, — while we might understand why sight should have been the favorite sense of the Spiritualistic philosophy, we should, at the same time, be compelled to admit that the eye is a somewhat clumsy organ. If the ultimate fibres of the auditory nerve had been supposed to be directly sensitive only to the vibrations of the fluid of the labyrinth, and if the functions of the *ductus cochlearis* and all its exquisite mechanism — which does instantly what the mathematician only lately learned to work out by Fourier's intricate formulæ — had been undiscovered, the explanation of the ultimate processes involved in the sensation of hearing would be scarcely more satisfactory than those of the sensation of color-perception now are.

Purkinje, Volkmann, Helmholtz, and others have found that, if two parallel fibres of spider's web, or two fine wires, be brought very close together upon a white ground, the intermediate white line seems to have a beaded, or zigzag, outline, when closely examined with one eye.

Assuming the cones to be arranged somewhat in the form of hexagonal cells in a honey-comb, this has been explained by supposing that the retinal image of such a line is so small that, as it falls across this musive surface, one minute section of it would excite only one cone, while the sections immediately above and below would cover halves of two adjacent cones, and, exciting both to activity, would appear twice as large.

Now, if the ultimate percipient elements be cones of three varieties of sensibility, corresponding to the colors red, green, and blue, or violet, it follows that the cones which perceive, *e. g.* green, must be much more widely dispersed over the retina, being at most only one-third of the whole number; and hence, with black lines upon green ground, or the reverse, we might fairly expect this beaded irregularity to be much greater than if all the cones were excited, as they would be by white lines of light. To test this, I gummed ultimate fibres of white silk upon a smooth piece of heavy black paper, as near together as I could distinguish them when the lens under which I worked was removed. By bending the paper gently backward, the fibres were drawn tense and straight. After some practice, in the morning, when the eyes were fresh, or even after closing them for a minute, later in the day, I could distinctly recognize that the outlines of the white fibres were wavy, and even beaded. Now, as near them as possible, parallel fibres of bright red, green, blue, and violet were fastened, and viewed in a similar manner, under stronger illuminations. The same wavy outlines were observed, though with somewhat greater straining of the eyes. It is quite certain that the curves were no larger, and no less frequent, than with the white fibres. Thus, if the cause assigned to these appearances be the true one, and if my observations be verified, it would seem that the hypothesis of three sets of cones must be abandoned.*

If, then, we do really reach the ultimate possible limits of surface-perception without approaching one step towards the analysis of white light into its elementary colors, the only remaining hypothesis seems to be that they are distinguished in different planes of the retina. This, indeed, is countenanced by the calculation of Helmholtz that, when the eye is accommodated for a white object at convenient distances, the focus of the violet rays is .434 mm., or twice the thickness of all the layers of the retina in front of the focus of the red rays. Indeed, on the undulatory theory, the difference of wave-lengths must itself be a function of perception, which cannot therefore take place in a mathematical plane. Analogies of light and sound at once suggested to me sympathetic vibrations of the minute segments of the retinal cones, whose diameters, according to Max Schultze's measurements, are about the same as those of the wave-lengths near the red end of the spectrum. Accordingly, the following series of observations on positive, or incidental after-images, which have never been very fully investigated, was made: —

A series of bright-colored pieces of paper, four inches square, were fastened to a long strip of pasteboard, in the order in which they occur in the spectrum: a movable slit, of somewhat less diameter than the squares of paper, allowed any color to be seen by itself, without the effects of contrast. Positive after-images of each of these colors were formed, first by opening the eyes as suddenly and closing them again as quickly as possible, about once in a second, eight or ten times, — an experiment which was afterwards varied by illuminating the squares in a dark room by an electric spark, and later by observing, in the same manner, a solar spectrum, cast by two prisms of rock salt.

Beginning at one end of the spectrum, and trying each color successively, it was observed that, near the middle of the spectrum, the first phase of the positive after-image is nearly or quite white.

To my own eye, this effect is somewhat greater with highly saturated blue than with green, which appears dazzling white even beside white paper. No noticeable paling of red or of violet could be observed. The experiment was afterward varied by getting a positive after-image of the whole of a short spectrum at once, the middle of which still seemed nearly or quite white. Thinking that this might be due to the greater intensity which spectra formed by most prisms seem to have to the normal eye near the middle, these spectra were thrown upon red and violet paper, which absorbed most of the green rays; but still the effect was the same.

---

* Of course, the purest colors obtainable in silk contain the whole spectrum, and the only precaution adopted was that of tiring the eye for the complementary color before fixating the fibres. Of ten High School boys, who were induced to try the experiment for several consecutive days, and, without being told what was expected, to draw the lines as they appeared, three represented them as wavy, and could observe no difference in the size of the curves in the white and in the colored fibres.

Now, if we suppose a series of sensitive elements — let us say disks, like the rattles on the tail of a snake — at the ends of the cones, each responding by sympathetic vibrations, or otherwise, to the action of waves in the light-ether, of corresponding length, the perception of white light would require the simultaneous agitation of all, or at least of several, groups of these disks. Let us assume also, for the present, that these disks are arranged in a spectral order, — those sensitive to red near the point, those sensitive to violet near the base, of the cone, — each disk being transparent to all waves of greater length than those to which it is best fitted to respond. If this were the case, agitation of a group of disks near the middle of what we will call the cone-spectrum might mechanically agitate the groups on either side, and thus give rise to a wave of disturbance, which, passing to both ends of the series, would cause a sensation of white, which the agitation of either end would not do to any such extent.

Again, it is well known that pressure, either mechanically applied, or caused by retinal congestion, often causes pure colored as well as white images. This has never been satisfactorily explained on the hypothesis of three sets of cones, or rods. So far as the effects of pressure have been observed on retinal purple of fresh eyes, the effect is always the same. If we assume that increasing degrees of pressure excite waves of disturbance of increasing length, involving a larger number of disks, we can readily believe that the effects of fatigue, determining the degree of instability of different segments along the cone-spectrum, would account for the various color-sensations thus produced.

Instead of three species of terminal organs, the modern form of Young's hypothesis assumes three sets of sensitive fibres, responding to the irritations of the three ground colors. The facts of red blindness afford, perhaps, the strongest ground for this theory. According to our hypothesis, however, red is perceived in the outer plane of the retina at the end of the cones. If we consider the delicacy and comparatively exposed position of these red disks among the coarser pigment cells of the choroid, and especially if we admit it to be proven that the two change their relative position with every irritation, we should expect that the ends of the cones would be often injured or undeveloped, as, indeed, the microscopist often finds them. How far the insensibility of the normal eye to the less refrangible red rays is due to the limit of retinal function, and how far to the absorptive power of the lens and humors, has never been determined. We should expect, however, to find some of the thermal rays just at or beyond the point of the external cone, perhaps limiting, and sometimes even impairing, its functions. Toward the violet end of the spectrum, there is good reason to believe that no solar rays enter our atmosphere which do not cause, at least, fluorescent sensibility in the retina.

Professor Fick has lately reinvestigated the facts of the color-blindness of the equatorial tracts of the retina, and frankly admits that the phenomena he has observed cannot be explained by the absence of a fundamental color. He endeavors, however, to preserve the hypothesis of three sets of fibres by arguing that the physical constitution of the eye is such that excitation must be considered as a function of oscillation. Thus, the longer ordinates of the curves representing the maxima of each of the three sensations in the spectral series of colors approach each other as the color-blindness here becomes complete, or as the angle of vision increases: so that, *e. g.*, a red ray, falling here, might appear yellow. Now, by assuming near the *ora serrata* either a shortening or an inclination of the cones, so that either the red disks are absent, or not reached by their corresponding rays, these phenomena, if we take into account the chromatic aberration of the ante-retinal eye, which Fick has entirely disregarded, can all be explained in a much simpler way. More accurate observations, however, than have yet been recorded, respecting the angle of inclination of the ray to the cone, and the amount and uniformity of shortening of the external cone near the front edge of the retina, are here needed.

The peculiar relation of green to the two other colors, as shown on the leverage curve, or chart of mixing, as reconstructed by Maxwell, has never been satisfactorily explained on the hypothesis of Young. Why have we here a curve, and not an angle, as at red and violet? or, in other words, why does the mixture of any two tones of green cause such a sudden and exceptional decrease in saturation?

When we consider the almost perfect integrity with which the green rays reach the retina, and its sensitiveness to them, we should expect not only a greater saturation than is observed in the spectrum, but also more shades and more distinct hues than we find upon the color table. The complementary hues of green are numerous and pronounced.

These unexplained facts, however, are very simply accounted for, when we reflect on the instability which the central position of the green disks would give them, and the readiness with which a wave of disturbance, starting here and passing each way, would produce the impression of an admixture of white light; while the abruptness with which the impression of green fades out, after the stimulus ceases, leads us to believe, according to the law of acoustic sensibility in sonorous bodies, that the *green disks give sympathetic response to a greater variety of wave-lengths than the red, or even the violet;* in other words, that the sympathetic function at the centre of the cone-spectrum is less specialized than at its ends. This, too, if rays are brought to a second focus in each cone, we should expect.

Passing to violet, we must believe that the retina is directly sensitive to its own fluorescence. This, Helmholtz says, is improbable. But, if fluorescence is a property of the anterior layers of the retina, why should the eye not be sensitive to it, as it is to the retinal blood-vessels, or to the almost constant stimulation of blood-color from other adjacent membranes? If, on the other hand, the light green which has been observed in a fresh retina, under the stimulation of ultra violet rays, is due to a complementary activity of the green disks, then, of course, the mind perceives it directly in the lavender gray which may be seen by a sensitive eye among the most refrangible rays. Of course, this question is greatly complicated by the fact that the lens is far more fluorescent, and scatters light blue rays all over the interior eye; and that even the cornea and vitreous humor aid in this general dispersion. While this would impair the distinctness of every violet image, it does not seem sufficient, without adding the effects of retinal fluorescence, to account for the evanescent touch of green which appears in ultra violet rays. It is possible, though hardly probable, that retinal fluorescence is a part of the function by which complementary colors are developed.

Before the late observations of Boll and Kühne, the theory that colors are to any extent reproduced in the eye would have been thought as baseless as the scholastic doctrine of visible species, or the Cartesian theory that colors are different rates of vortical motion. Boll now, however, not only insists that we must choose between what he terms the interpretation and the identity theories, but gives his vote for the latter. The great interest which the psychologist feels in these investigations is because this question is at least involved here. While it would be premature to say that all the observations thus far can be interpreted upon the hypothesis of a cone-spectrum, it seems quite certain that they cannot be interpreted in accordance with Young's theory.

It is, of course, yet possible that retinal purple is merely protective when the retina is most sensitive; viz., after rest. It is possibly connective tissue between the disks. It is, again, quite possible that its changes are connected with the perception of light and shade, and not at all with that of color. On the one hand, the fact that pressure causes the same sort of bleaching as light; that the color is chiefly confined to the external members of the outermost retinal layer, while near the vitreous body the cones and rods are nearly colorless; the fact that fluid solutions of retinal purple can be made only by a substance which causes the disks to fall apart, in Kühne's language, like a roll of coin suddenly unfastened; its high refractive power, — all these facts point decidedly toward the photo-physical explanation. On the other hand, we must not forget that the fact that retinal purple can be dissolved and filtered; the fact that perception probably takes place long before any sensible bleaching of the retina occurs; that colors are represented only by more or less paling, and never by changes of hue in the red substance; that it seems to be confined to the rods, and that pigment cells and the colored oil drop in the base of the outer members seem to undergo concomitant changes, perhaps regenerative, perhaps participatory; the fact that vinegar changes the red to instant yellow, — these facts, while they do not seem, as Kühne urges, to compel the belief that the retina is a photo-chemical workshop, or that the red is independent of all structural changes, do show us that we are here on the boundary line between chemistry and physics, and that the interpretation of each may be partial. Observations on retinal purple, and the fact that continued pressure on one eye causes all objects for a time to seem tinged with violet, would incline us to believe that the action of light on the cone-disks causes increased tension, possibly shortening instead of, or more probably along with, sympathetic vibration.*

---

* On the photo-physical hypothesis, the almost constant action of red rays from the blood would tend to relax tension, — perhaps bringing a large number of disks into distances from each other corresponding to the length of the red instead of to that of the shorter waves, — and the retinal purple might then be due to the same cause as the color of thin plates; while the white which occurs with protracted illumination of a fixed eye would be physiologically analogous to tetanus; and the observer would see all the colors superimposed, producing the impression of white. This, again, would indicate that the phenomena of fatigue are to be explained, in part at least, by nervous exhaustion, and not entirely by failure of mechanical response in the terminal apparatus; and thus we are brought, by a very direct, scientific path, to the old question of phosphorescent effects in the eye.

Volkmann, Goethe, Brewster, and many others, have claimed to be able to distinguish with one motionless eye two component parts of a mixed color. Helmholtz urges that this is always a matter of judgment, and not of sensation. We are used, he says, to seeing things in the changing lights and shadows of morning, noon, and night, and by artificial illumination; and so unconsciously acquire the ability to judge what is due to the medium, and what comes from the object; and thus can often do so correctly the first time, when thin, white paper is spread over a colored surface. Wundt urges against Zenker's ingenious theory, that we ought to see white light as mixed. Now, in the first place, it is by no means proven that the eye cannot be trained to see one color through another at a distance from it, — which is the most favorable form of mixing; but even here each shade of a composite color may have a different local sign, while, as in our hypothesis, the elastic mechanical action of disks on each other — lying, as they do, so close together that no microscope can distinguish them in a fresh retina — prevents distinct perception. Investigation is much needed here. Meanwhile, we must not forget that the retina is not the only surface where different modes of irritation coalesce in a single sensation, and that the difficulty may be solely due to inadequate cultivation of attention and discrimination.

Our theory thus involves a redistribution of the causes of many well-known phenomena of vision. We must distinguish, first, those due to direct action of light on sensitive disks; second, those due to the action of these disks on each other; and, last, those due to the neural action thus occasioned: and the problem now before us is to determine how far such phenomena as after-images, contrast, persistence of impression, &c., are due to each of these influences. Such familiar facts as that change of brightness causes change of hue; that pale and dark colors are more contrasted than those that are full; that greater intervals intensify and emphasize colors, while small differences in tone seem most contrasted, — would indicate that contrast is not, as has been lately claimed, all a matter of subjective judgment, but that it may be due, in part, to the second of these causes. Complementary after-images, it is quite certain, cannot be explained by any theory of musical harmonics; for the musical fifth would give us a greater, the third a less, than the complementary interval on the color scale. We should expect, if the disks respond by vibration, that their motion would be far less rapid than that of light waves, corresponding perhaps as a very small multiple, or as a lower harmonic or difference tone; or, again, there may be one curve for the elasticity of disk action, or of the tissues connecting the disks, and another different curve representing neural fatigue; so that there would be two waves of excitation along the cone-spectrum, each followed at different intervals by slower, damping waves of fatigue: and it seems quite possible that the combined effects of both must be estimated in explaining all species of after-images. Many circumstances, which will readily occur to those who have followed us thus far, would lead us to believe that persistence of impressions would be found due more to the terminal apparatus than to the nerve action. The functions of the rods still remain unexplained. It has been suggested that, as white light is analogous to noise, the functions of the rods correspond to what was, until lately, supposed to be that of the vibratory hairs or the otoliths of the labyrinth. The very fact that these disks are smaller and more numerous and more uniform in size, while they contain apparently less nervous elements, suggests indeed that their function is to emphasize position more minutely than is done by the cones. That they do not perceive color is made to some extent probable by the fact that retinal purple, which seems to exist only in them, is not specifically modified by color as such; while, finally, if there is any reason to believe, as has been suggested, that cones are modified or developed rods, then the surprising theory of Hugo Magnus, which is so strangely countenanced by philological facts, — viz., that the color-sense has been developed out of simple perception of light and shade within the historic period, and in the spectral order, beginning with red, and with some corresponding loss in the accuracy of form-perception, — has at least one physiological fact in its favor.

Many other possible but unverified analogies with the ear are suggested: *e. g.*, may there be found any such correspondence between the length or number of cones and the brilliancy of colors developed among lower animals — and especially birds — by sexual selection as has been observed between the length of the *ductus cochlearis* and the development of songs and love-calls? Is there any special reason why, as the lower notes affect only the vibratory fibres most remote from the entrance of the labyrinth, so the red rays pass the other sensitive disks, to be perceived at the further end of the cone?

It is high time to remember that our theory can be called, at most, only probable, until the course of the rays through the retina can be more accurately traced. First, let us suppose light to undergo a special and final refraction, in the substance of the retina itself, before it is perceived. This is rendered highly probable by the great refractive power of the cone substance and of the retinal purple; by the fat globules and lentiform bodies observed in the cones of birds and reptiles; and by the bright appearance of the points of the cones, as seen from the back of an illuminated retina. This would be necessary, if rays of each color were to be focused on their appropriate disks. The distance between the focus of red and that of violet, as formed by the lens and humors, would then have to be reduced to, let us say, one fifteenth its estimated extent. This, again, would require such a dispersive surface as would bring rays, coming to different foci from different directions, into approximate parallelism; and, finally, a very strongly converging, and at the same time dispersive, power. Both these problems are theoretically solvable by the calculus of geometrical optics; but there still remains some doubt whether such a surface as is required in the first lens could really exist, and whether any known substance combines the high degree of refractive and dispersive power requisite for the second. It is, of course, conceivable that a substance might exist which should refract rays of one end of the spectrum, and transmit those of the other unaltered; and it is, again, very probable that each disk has a refractive power of its own. But, fortunately, none of the above suppositions are necessary. We may suppose that each disk responds to its own ray, from whatever direction it comes. In that case, the tardy action of red rays in producing their maximum sensation might be explained, in part, by the smallness of the red disks.

It is by no means necessary, as was assumed by the critics of Zenker's theory, that the thickness of the disks should in any way correspond to the length of the waves of light, or even that the phenomena of interference should be invoked. The difference may lie solely in size; it may depend on the angle of incidence; or, again, there may be such a special sensibility among the disks, and such minute accuracy in the refractive apparatus, that every red ray is thrown directly upon the sensitive point of its own disk, and that even another ray thrown there would seem to have the hue corresponding to the disk. All we want is a ponderable ether; while the fact that millions of vibrations are necessary before the faintest trace of color can be perceived sufficiently indicates its tenuity as compared with the medium of sound-waves.

The number of disks must be, at least, several hundred. Aubert was able to distinguish one thousand hues in the spectrum. Goblet and Rood believe we can learn to distinguish many million hues and shades. So it is probable that we shall here have to resort to the same explanation which Helmholtz gives of the fact that musicians can perceive one sixty-fourth of a semi-tone, which is less than the difference between the pitch of two of Corti's arches. In the one case, the two disks, as in the other the two arches, nearest attuned to the wave-length, would be excited, — the nearest one the most strongly; so that we shall never be able to perceive the steps or jumps which correspond to the difference between the ultimate percipient elements in either the tone or color scale.

The histologist Hensen long ago conjectured that perception took place at the outer segment of the cone, because the field of vision is made up of points so widely separated in comparison with their diameter. It has more recently been urged that the cones are not nervous substances, and that no fibres can be found running from their external segments. To this it can only be said that, if the size of the fibres bears any proportion to the length of the wave, observations on the ultimate nervous elements of the ear would teach us that comparatively large bundles of ultimate retinal fibres would still be invisible under the highest microscopic powers. The two hundred and fifty thousand fibres of the optic nerve may themselves be very complex. Our theory only adds a third to the two yet unexplored intervals along the diameter of the retina, which all who believe that the cones share in the act of visual perception admit must be somehow traversed by sentient processes.

If, then, certain phenomena, like colored shadows, or the subjective light of the closed eye, and many others, may be partly explained by the action of disks on each other; especially, if colors shall be found, in any sense, to be reproduced on the retina, — it may be that some of the many ingenious but mistaken color theories which have abounded in the world ever since Plato's day may have something to teach us which has been overlooked; for instance, Schopenhauer's, which has at least the merit of being purely physiological, while his formulæ of divisible remainders, and of qualitative and quantitative retinal activity, may be applied at once.

Chodin's observation, that moderate pressure always excites a sensation of green, whether on a black or white ground; Wheatstone's discovery, that on a smooth surface of red and blue squares the red seem raised; the fact that a distant landscape, viewed with inverted head, seems more like a flat surface, but more brightly colored, so that color and the third dimension of space seem reciprocal functions, — these and many other observations seem more or less fully explained by our hypothesis, which at least suggests new paths of investigation, and may perhaps even justify the question how much better, at this stage of our knowledge, we are really fitted to decide whether a color-scale is possible, than musicians who lived when a three-stringed harp was the most perfect instrument were to discuss diatonic intervals.

The writer desires to express his unusual obligations to Professor H. P. BOWDITCH for suggestion, criticism, and supervision of laboratory work, and to Dr. B. JOY JEFFRIES for the free use of his valuable library.